Electrochemical Hydrogen Compression (EHC) solutions for hydrogen infrastructure

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HyET is developing Electrochemical Hydrogen Compression (EHC) as a highly efficient solution for the broader deployment of hydrogen infrastructure. This innovative technology is suitable for hydrogen refueling stations for vehicles, and for the injection of renewably produced 'green' hydrogen into the natural gas pipeline grid.

Energy supply remains a hot topic with strategic, economic, social and environmental importance. HyET was founded as an SME (small/medium enterprise) in 2008 by the late Erik Middelman in Arnhem, the Netherlands, and targets the development of Hydrogen Efficiency Technologies enabling high compression, thus contributing an essential puzzle piece towards a sustainable energy supply chain.

Hydrogen compression

Currently, mechanical compression of hydrogen is achieved using diaphragm pumps for capacities up to 1 kNm^3/h, and piston pumps for capacities up to 1 MNm^3/h. (Also including screw and turbo compression at very large scale.) The compression process is adiabatic, and hence divided into stages to reduce temperature excursions and improve energy efficiency.

Typically, the friction of seals and valves adds 20% to the energy requirement, adding up to approximately 6 kWh/kg for compression from 1 to 40 MPa (10 to 400 bar). HyET's electrochemical compression process is isothermal and single-stage, having the potential to reduce this energy requirement down to 3 kWh/kg. However, this article aims to show that the surplus value goes much further.

Electrochemical pump

Hydrogen transport using an ionic displacement was already known in the 1960s according to insiders, discovered during the development of the first Nafion®-type membranes for fuel cells.

The HyET Electrochemical Hydrogen Compressor is highly efficient, compact, scalable, and can handle a wide range of input pressures with immediate response.

There was no economic interest in this feature at that time, but there have been some academic publications on the subject. Continued development and progress in fuel cells now make electrochemical hydrogen pumping technically and economically feasible. Different from fuel cells and electrolysis, the chemical reaction itself does not deliver new products nor energy: hydrogen goes in, hydrogen goes out, or vice versa if the direction of the electrical current is reversed. It's as simple as that.

Hydrogen use

Global hydrogen consumption is estimated at 50 Mtonne/yr, of which only 2 Mtonne/yr is produced from electrolysis; the majority is produced from hydrocarbon sources such as gas (24 Mtonne/yr), oil (15 Mtonne/yr), and coal (9 Mtonne/yr).[1]

Hydrogen consumption in the Netherlands is huge, thanks to the chemical industry including refineries around the Rotterdam area and the steel industry along the west coast. The eastern side of the country groups a number of smaller companies focusing on hydrogen as an energy carrier, such as Nedstack (fuel cells, also founded by Erik Middelman), HyGear (steam methane reforming, SMR), and HyET. The local municipality in Arnhem strongly supports this energy initiative, having its roots in natural gas supply, electrical trolley buses, and being situated on a highway corridor towards Germany. Hydrogen could be the next renewable fuel.

Hydrogen refueling stations

The Netherlands has a handful of hydrogen refueling stations (HRS) installed in Arnhem, Eindhoven, Amsterdam, and Petten (Energy Research Centre of the Netherlands, ECN), and there are plans to build more in Delft and Rotterdam. HyET is participating on a national level, but is focused primarily on the international market. The company is partnering with key stakeholders in the field to advance specific applications ranging from commercial stations (>200 kg H_2/day) down to home refueling (2 kg H_2/day). Our modular stack design easily conforms to centralised as well as distributed utilisation, because a multitude of units can operate in parallel as one.

Energy storage

Our PHAEDRUS project – funded by the European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) – aims to realise in 2015 a commercial hydrogen refueling station featuring an optimal combination of mechanical and electrochemical compression up to 100 MPa (1000 bar).

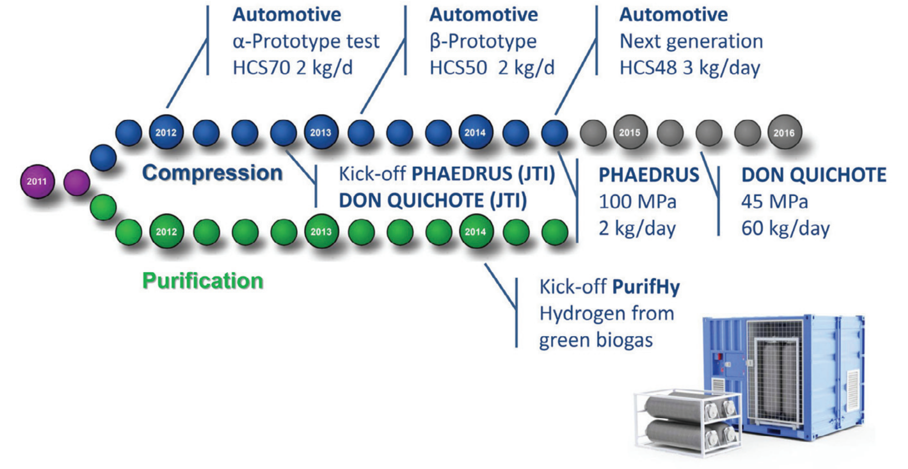
In the 'Don Quichote' project (also FCH JU) the target is to capture renewable wind and solar energy, and store this in the form of compressed hydrogen (60 kg H_2/day at 40 MPa/400 bar), then dispense it when needed to a fuel cell system to make electricity on demand. In this latter project HyET will investigate how much compression energy can be recovered during decompression, making the overall energy cycle even more efficient.

Easy electrochemical compression

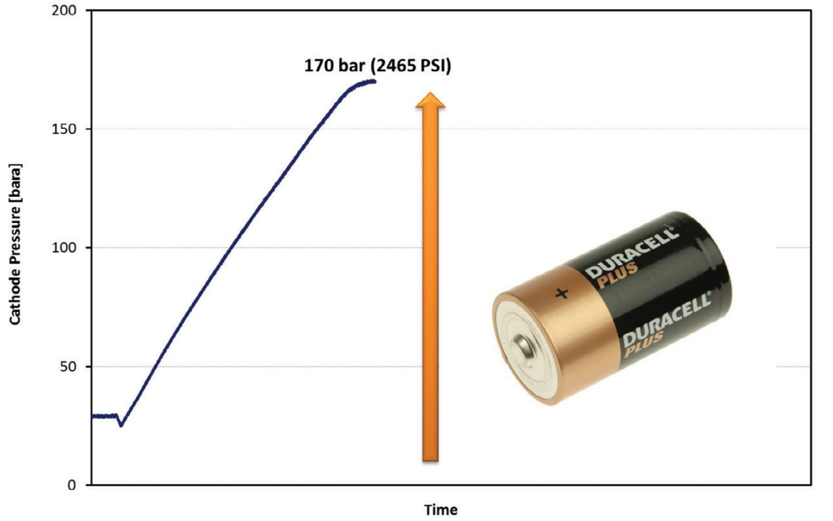
One experiment illustrates how easy electrochemical compression is. We took a battery (1.5 V, D-cell type) – the type you find in a certain 'battery-brand bunny' – and hooked it up to a three-cell stack. To our astonishment, the pressure increased from 2.5 to 17 MPa (25 to 170 bar) in the time it takes to drink a coffee. Note that standard 50 litre gas cylinders contain hydrogen at 20 MPa pressure (200 bar). Reflecting on our observation, the 1.5 V provided proved to be overkill, because at this pressure the compression energy translates to only 80 mV Nernst voltage over all three cells. This stored 80 mV can be recovered during decompression, just like you would expect from a rechargeable (hydrogen//hydrogen) battery.

Compression principle

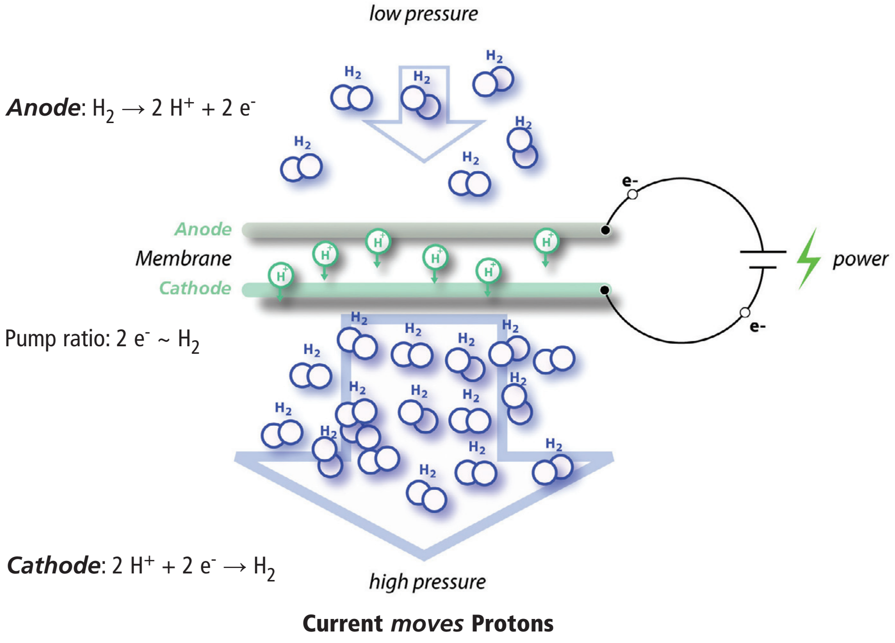
Electrochemical compression of hydrogen is based on the following mechanism. Hydrogen is supplied to the membrane surface, where a platinum-alloy catalyst splits the molecule into protons. The electrons are transferred via an external circuit to the opposite catalyst



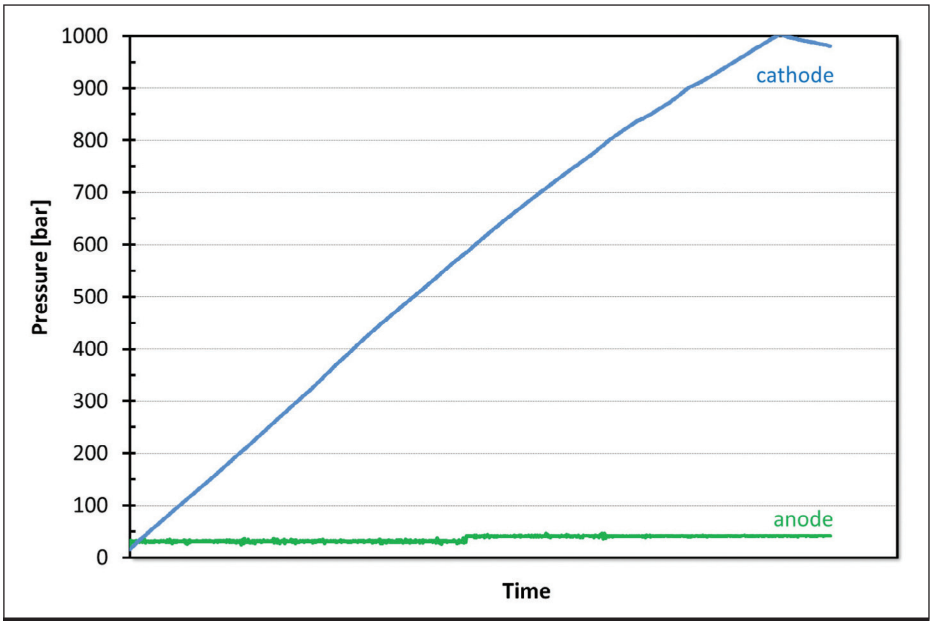
HyET is involved in several international and national projects to develop and demonstrate the Electrochemical Hydrogen Compression (EHC) technology.



A simple experiment using a single battery showed that Electrochemical Hydrogen Compression can increase the pressure from 25 to 170 bar in just a few minutes.


low pressure
Anode: $H_2 \rightarrow 2\,H^+ + 2\,e^-$
H_2
e-
Anode
Membrane
Cathode
H^+
power
Pump ratio: $2\,e^- \sim H_2$
e-
Cathode: $2\,H^+ + 2\,e^- \rightarrow H_2$
high pressure
Current moves Protons

Electrochemical Hydrogen Compression uses direct current to pull hydrogen through an impermeable membrane, very efficiently and highly selective for hydrogen.



HyET has demonstrated single-stage compression to a quite remarkable 1000 bar using Electrochemical Hydrogen Compression.

layer on the other side of the membrane. A current is used to force the protons through the membrane, and to recombine as hydrogen molecules on the output side. Effectively, this induces mass transport of hydrogen, and only hydrogen, enabling simultaneous purification. The take-home message is: one electron equals one proton, equals half a hydrogen gas molecule.

Compression is achieved by pumping more hydrogen from input to output, while restricting its exit using a back-pressure controller. Simply put: if you put your finger on the input, you can feel the vacuum being drawn, and if you put your finger on the output, you feel the pressure build up. This pressure will increase as long as the electric current continues to transport more hydrogen, until the pressure is relieved externally. HyET has demonstrated that single-stage compression to 100 MPa (1000 bar) is possible, which is quite remarkable knowing that a column of 10 km is sitting on a thin polymer membrane. For most, this concept does not feel natural.

Storage by adsorption

High-pressure hydrogen storage is driven by the automotive sector adopting the 70 MPa (700 bar) standard, in order to maintain sufficient range of the vehicles without sacrificing too much space. Storage at lower pressures is possible using chemical binding or physical adsorption on metal hydrides or Metal Organic Frameworks (MOFs). However, if high pressure no longer poses a problem, considering high-strength carbon-fibre-wound tanks and the discussed compression capability, it would seem simplest to bottle the hydrogen as is. Whatever the final solution, HyET's electrochemical compression and decompression is flexible enough to extract and/or deliver hydrogen over a wide range of pressures.

Balance of properties

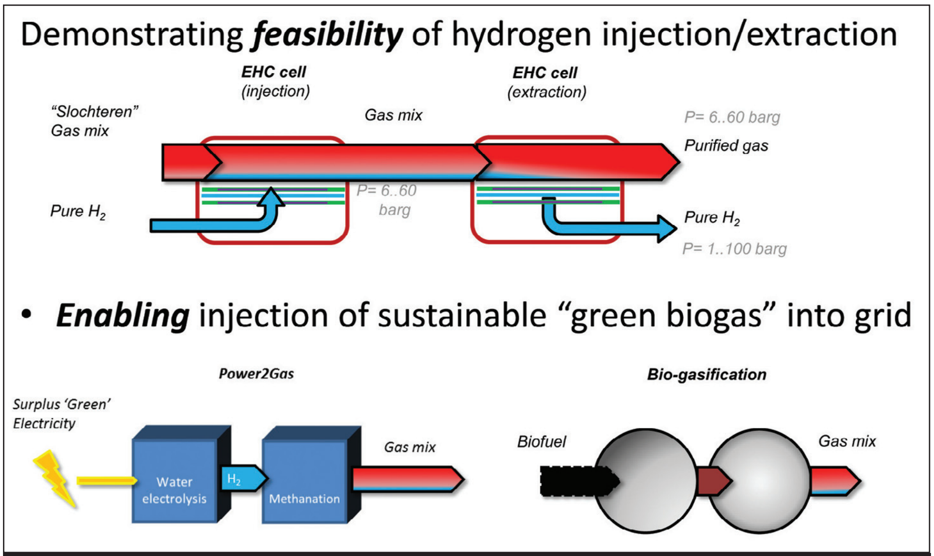
The limit for pressurised hydrogen is dictated by a balance of the following membrane properties. First, the strength of the hydrogen confinement chamber, where the membrane is the weakest link. Second is the permeability of the membrane, resisting the permeation (so-called back-diffusion) of hydrogen in its molecular form. Thirdly, proton conductivity dictates the maximum forward transport rate compensating for any leakage or hydrogen losses. Clearly, the membrane is key. HyET has a range of dedicated, proprietary membranes in stock, and continues membrane material development.

Gas purification

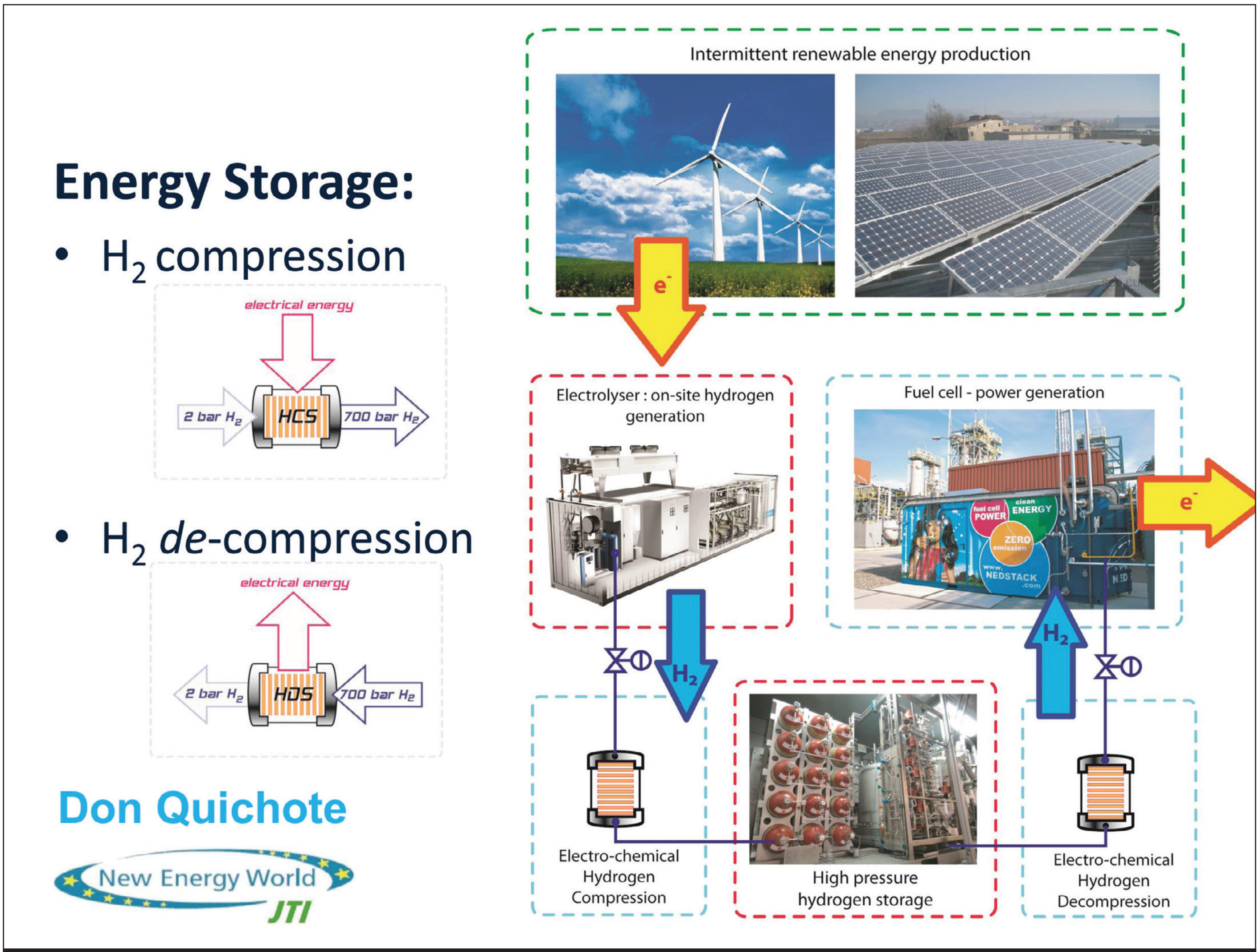
Polymer electrolyte membrane (PEM) electrolysis technology delivers the highest purity of 99.9999% after drying. Hydrocarbon-based reformate compositions typically contain approximately 70% hydrogen, and require cleanup using pressure swing adsorption (PSA) and/or membranes to achieve hydrogen purities suitable for fuel cell applications. HyET's Electrochemical Hydrogen Compression technology has shown that it can extract the wet hydrogen directly from a variety of sources and deliver this at high purity and high pressure. So far, we have managed purification despite carbon monoxide (CO) concentrations up to 12%, and even hydrogen sulfide (H_2S). Since all gas compositions are customer-specific, joint development always starts with lab-scale tests.

Energy conversion

The coupling between hydrogen and methane deserves some more attention. Both gases are used as fuel, but methane is easier to compress and distribute through the extensive pipeline network in Europe. This network is particularly extensive in the Netherlands due to the discovery of the Slochteren natural gas resources (Groningen gas field) in 1959. This network expands into northern Europe and connects directly to the pipeline from Russia. The Dutch government has benefited greatly from natural gas sales, and would like to integrate this gas network as part of the future energy supply security strategy. Rigorous standards demand specific gas compositions based on methane. Hence, it is logical to first consider introducing



HyET is engaged in injection and selective removal of hydrogen from natural and 'green' gas mixes through the Dutch 'PurifHy' project for Power2Gas energy storage.



The Don Quichote project is demonstrating renewable hydrogen production; HyET will investigate how much compression energy can be recovered during decompression.

'green' (i.e. renewably produced) methane gas into the mix as a sustainable, carbon-neutral alternative. Note that an energy equivalent of 500 GW can be buffered in these pipelines, without even considering re-injection of green gas into the ground for later use.

Power2Gas

The hydrogen-methane relationship actually goes both ways. Making methane again from captured CO_2 takes energy and requires hydrogen. The resulting green gas will cost significantly more than the fossil equivalent, a cost that can only be offset using hefty CO_2 taxation. Using hydrogen directly offers potential solutions to a sustainable energy infrastructure, that does not include fossil carbon, and hence is not weighted down by CO_2 regulations. Experiments have shown that injection of hydrogen into the natural gas pipeline up to 20% is feasible. It is important to note where hydrogen is injected, whether in major distribution lines or in local residential pipelines, because a consistent supply and composition are vital for end-user satisfaction.

PurifHy project

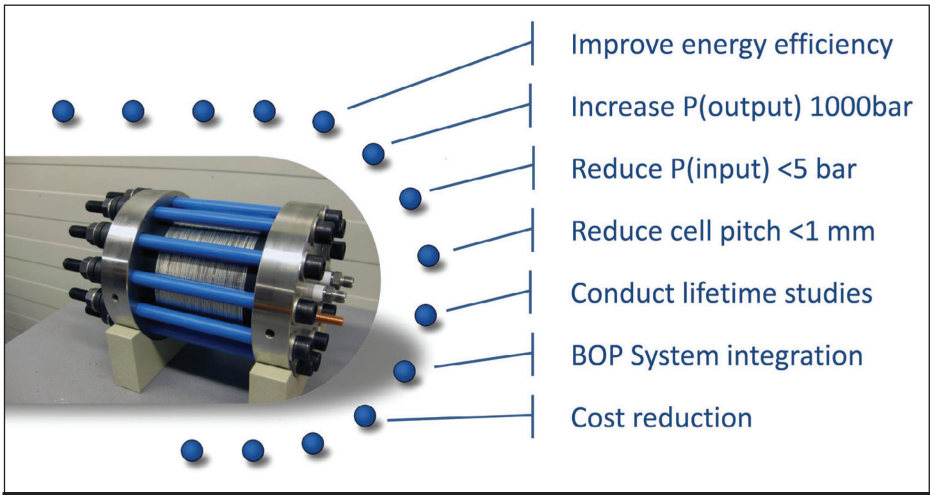
HyET is engaged in injection and selective removal of hydrogen from the natural and green gas mixtures through the Dutch funded 'PurifHy' project. Partners in this two-year project are Stedin (network distributer), DNV/GL (gas qualification agency), the Energy Research Centre of the Netherlands (ECN, government lab investigating torrefaction), and HyET. Stedin and DNV/GL are together realising the Power2Gas (P2G) project, creating green methane gas from CO_2 with hydrogen traces potentially exceeding the regulatory natural gas standard. HyET aims to extract the surplus hydrogen.

If successful, green methane gas can be injected and distributed using the existing natural gas pipeline network. Going forward, this work will point out opportunities for utilising hydrogen in the grid gas mixture while providing valuable field experience in the field using new technologies.

Distributed power

Energy buffering capability helps smooth the economic balance between energy supply and demand, as is evident from the volatile electricity price. Structural grid balancing technology is called for with more variable solar and wind energy sources being connected. A solution is presented with the ability to convert efficiently between different energy types, including electricity, (gaseous) fuel, and heat, provided that temporary accumulation (storage) is enabled. Storing energy as fuel has always been preferred.

Hydrogen has the highest energy capacity per weight, but has until now been difficult to contain. Together with the electrochemical conversion between hydrogen fuel and electricity and instant coordination through the internet, it is now possible to command a distributed power station.



HyET's EHC roadmap anticipates continuing incremental improvements for the modular EHC unit, targeting customer specifications, capacities, and applications.

Outlook

These are exciting times to be pioneering electrochemical compression and developing technology into novel products. Our small, technically oriented team can make incremental iterations in quick succession. Parallel development of cell hardware and membrane 'software' has contributed greatly to our success, ensuring mutual compatibility under the high stress of compression.

We have come to understand that materials research and development is inevitable to enable next-generation products. A collective of academia, government, and energy businesses need to join forces to further explore these challenging opportunities around integrating hydrogen in the existing energy infrastructure. In this way HyET can tailor our puzzle piece to fit in the bigger picture.

Reference

1. Arno A. Evers: National Hydrogen Association, 2008.

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PHAEDRUS project: www.phaedrus-project.eu

Don Quichote project: www.don-quichote.eu

Fuel Cells and Hydrogen Joint Undertaking: www.fch-ju.eu

PurifHy project: www.tki-gas.nl/projecten/teg0413002 (in Dutch)

Patents

SOFC interconnect coating with transition metal oxide ($MnCo_2O_4$ or $CuMn_2O_4$), excellent sintering

Assignee: **NGK Insulators Ltd, Japan**
Inventors: M. Ohmori et al.
Patent number: US 8617769
Published: 31 Dec. 2013 (Filed: 22 Oct. 2010)

Oxygen evolution reaction catalysts that reduce corrosion on PEMFC cathode catalyst layers, to improve startup/shutdown durability

Assignee: **General Motors, USA**
Inventors: S.G. Yan et al.
Patent number: US 8617770
Published: 31 Dec. 2013 (Filed: 3 Sep. 2008)

PEMFC MEA with two first stacked electrode catalyst layers with different PEM content ratio

Assignee: **Toppan Printing Co, Japan**
Inventor: M. Oota
Patent number: US 8617771
Published: 31 Dec. 2013 (Filed: 26 Feb. 2010)

Method for producing polyhedral Pt nanoparticles, e.g. for PEMFC electrode catalysts with excellent catalytic activity

Assignees: **Aisin Seiki Co, Japan,**
Toyota Motor Corporation, Japan
and **Doshisha University, Japan**
Inventors: T. Kamizono et al.
Patent number: US 8618019
Published: 31 Dec. 2013 (Filed: 25 June 2009)

Identifying fuel cell defects in system for testing multiple SOFCs

Assignee: **Teradyne Inc, USA**
Inventors: A.J. Suto et al.
Patent number: US 8618810
Published: 31 Dec. 2013 (Filed: 4 Mar. 2011)

Fuel cell simulator for predicting power generation performance, with modeling of catalyst layer from geometry and property data

Assignee: **Toyota Motor Corporation, Japan**
Inventors: M. Fujiuchi et al.
Patent number: US 8620637
Published: 31 Dec. 2013 (Filed: 12 Feb. 2009)

SOFCs and electrolysers utilising nanoscale metal oxide films for dense ultrathin electrolyte layers and electrode coatings

Assignee: **C3 International, USA**
Inventors: M. Deininger et al.
Patent number: US 8623301
Published: 7 Jan. 2014 (Filed: 8 Apr. 2009)

SOFC system with electrical heater to maintain operational internal temperature in hibernation mode

Assignee: **Cummins Power Generation, USA**
Inventors: C. Vesely et al.
Patent number: US 8623533
Published: 7 Jan. 2014 (Filed: 14 Sep. 2007)

Aircraft (PEM) fuel cell system with suction module to draw oxygen through cathode in flight

Assignee: **Airbus Operations, Germany**
Inventors: L. Frahm et al.
Patent number: US 8623559 [**see 8623566**]
Published: 7 Jan. 2014 (Filed: 24 Sep. 2008)

Control of heat balance in stacks in SOFC system, using recuperator unit for heat exchange

Assignee: **Convion, Finland [was Wärtsilä]**
Inventors: K. Åströ et al.
Patent number: US 8623560
Published: 7 Jan. 2014 (Filed: 4 Dec. 2012)

Acid dilution device in condenser of phosphoric acid fuel cell

Assignee: **ClearEdge Power, USA**
[formerly UTC Power, *see page 8*]
Inventors: T.B. Avis et al.
Patent number: US 8623561
Published: 7 Jan. 2014 (Filed: 29 June 2009)